Laboratory-Scale Steam Power Plant Study – Rankine Cycler™ Effectiveness as a Learning Tool and its Component Losses.

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Abstract

The *Rankine Cycler*™ steam turbine system, produced by Turbine Technologies, Ltd., is a table-top-sized working model of a fossil-fueled steam power plant. It is widely used by engineering colleges around the world.

The objectives of this paper are threefold. First, undergraduate students that have used the *Rankine Cycler* were surveyed to assess the effectiveness of the device as a learning tool. The results of the survey can be applied so that the equipment is used in the undergraduate curriculum in the best possible manner.

Inevitably, when a power generation plant is scaled-down and it has few efficiency-enhancing components (e.g. lack of feedwater heaters, etc.), energy losses in components will be magnified, substantially decreasing the cycle efficiency. Although the *Rankine Cycler* is a useful tool for teaching fundamentals of thermodynamics, fluid mechanics, heat transfer, and instrumentation systems in an undergraduate laboratory, a comprehensive analysis of the equipment has not been performed. This analysis would be useful to faculty and students who use the equipment and would also be useful to potential customers of Turbine Technologies. Faculty and students at two different universities have begun a comprehensive analysis of the *Rankine Cycler*. As an initial effort, the results of a parametric study of the effects of component losses on cycle efficiency are presented. Considerations in this study include boiler efficiency, turbine internal efficiency, turbine volumetric efficiency, mechanical efficiency, electric generator efficiency, boiler-to-turbine line losses (pressure and heat), and turbine-to-condenser line losses. In addition, proposals are made for experimental determination of *Rankine Cycler* component performance.

Finally, in addition to the learning assessment and parametric study, future studies are outlined to complete a comprehensive analysis of the Rankine Cycler.

1. Introduction

Perhaps the leading news headline from the summer of 2003 was the northeast U.S. blackout. Major cities, New York, Boston, Toronto, and Cleveland were without electricity for a couple of days. Many parts of the Detroit metro region were without electricity for more than 3 days. Questions on many people's minds included: Why was there a blackout? What caused it? Those were difficult questions to answer for the general public simply because many of the people asking the questions do not know from where the majority of our electricity comes.

Almost everyone with a degree in mechanical engineering does have an idea how the majority of the electricity in the U.S. is generated. Unfortunately many mechanical engineering graduates have only a vague idea. Nonetheless, each mechanical engineer, when they were a student was required to learn something about the thermodynamic cycle (known as the Rankine Cycle) that uses steam to produce the majority of the electricity in the U.S. For many, this was simply a pencil-and-paper exercise.

While the blackout and ongoing power capacity problems occurring in locations throughout the U.S. (e.g. California) are attributed more to distribution than generation, there is an educational tool available to mechanical engineering professors who wish to reinforce the concepts of steam power generation. The "Rankine Cycler™", produced by Turbine Technologies Ltd. of Chetek, Wisconsin (hereinafter called the "RC"), is a tabletop steam-electric power plant that looks and behaves similarly to a real steam turbine power plant (see Figure 1). About the size of an office desk, the plant contains three of the four major components of a modern, full-scale, fossil fuel fired electric generating station: boiler, turbine, and condenser. Using only propane and water, the plant will actually generate electricity. Note that the RC does not operate in a true cycle (the pump is missing); it is a once-through unit (see Figure 2). Nonetheless, many of the key issues regarding steam power generation are illustrated by the device. There are other steam power generating educational tools available from various companies, but these operate with a reciprocating piston instead of a turbine. These other educational units are also more costly and often larger.

The RC is completely outfitted with sensors to measure key properties. The data is displayed in real time on a computer so that students can instantaneously observe the behavior of the plant under differing scenarios. The unit operates by burning propane to convert liquid water into high pressure, high temperature steam (over 380°F and 130 psia) in a constant volume boiler (see Figure 3). The steam flows into a turbine causing it to spin (see Figure 4). The turbine is attached to a generator which produces electricity when spun. The generator will produce approximately 5 Watts. The steam (which has now used up most of its energy to spin the turbine/generator) leaves the turbine and flows into a condenser where part of it (about $1/6^{th}$) is condensed into liquid water. The uncondensed steam is vented to the atmosphere. Unfortunately, because of the small scale of the unit, thermal efficiency is inherently very low (on the order of several tenths of one percent).

Figure 1: The Rankine Cycler. Note that the newer models include a USB port data acquisition system and laptop computer that is mounted to the tabletop[2].

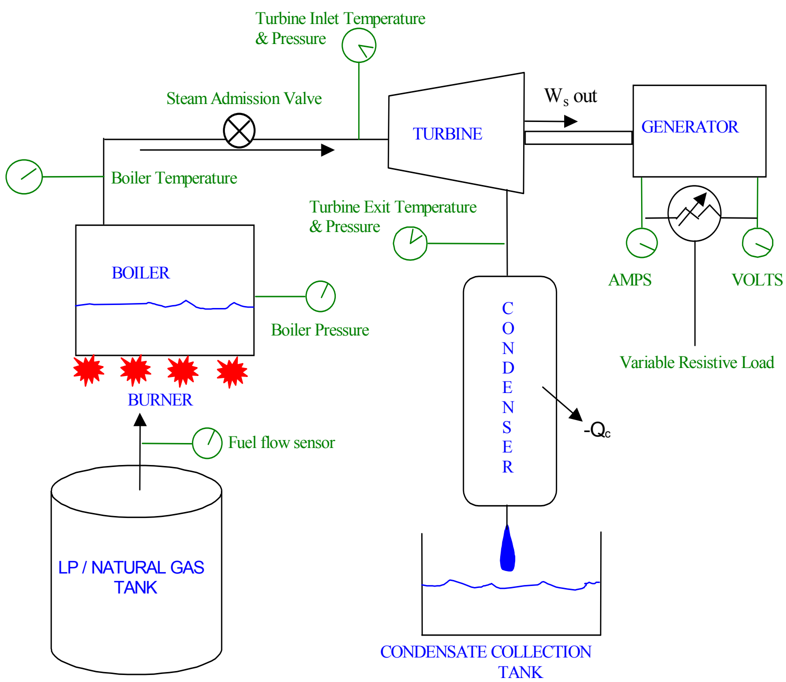

Figure 2: Schematic of the Rankine Cycler[2].

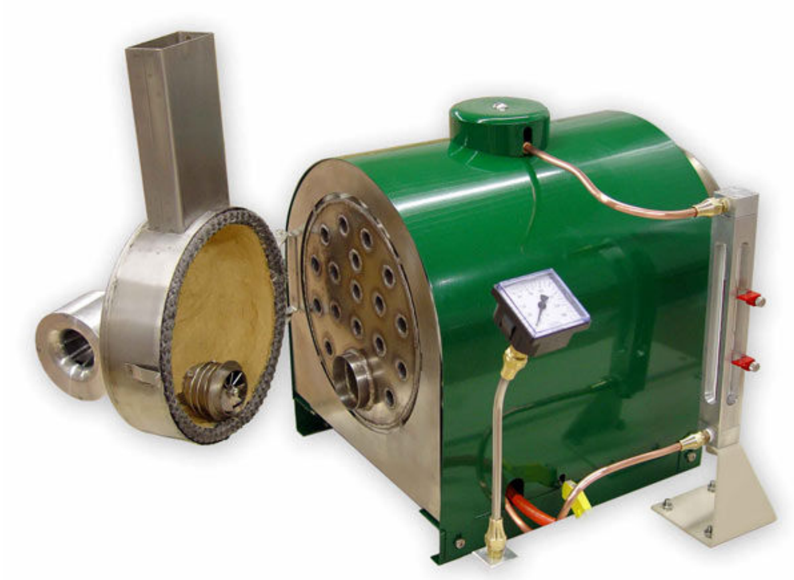

Figure 3: The dual pass, flame-through tube type (constant volume) boiler, with super heat dome[2]. See Appendix A for more details.

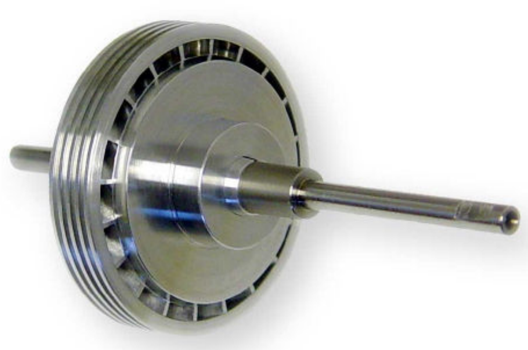

Figure 4: Axial flow steam turbine outside of its casing[2]. See Appendix A for more details.

A. Objectives

Lawrence Technological University (LTU) and the University of Evansville (UE) want to ensure that each graduating mechanical engineer has a good understanding of power generation. To accomplish their goal, LTU and UE have begun a study to measure the effectiveness of the RC. Therefore, the objectives of this paper are threefold. First, undergraduate students that have used the RC were surveyed to assess the effectiveness of the device as a learning tool. The results of the survey can be applied so that the equipment is used in the undergraduate curriculum in the best possible manner.

Inevitably, when a power generation plant is scaled-down and it has few efficiency-enhancing components (e.g. feedwater heaters, etc.), energy losses in components will be magnified, substantially decreasing the cycle efficiency. Although the RC is a useful tool for teaching fundamentals of thermodynamics, fluid mechanics, heat transfer, and instrumentation systems in an undergraduate laboratory, a comprehensive analysis of the equipment has not been performed. This analysis would be useful to faculty and students who use the equipment and would also be useful to potential customers of Turbine Technologies. Faculty and students at two different universities have begun a comprehensive analysis of the RC. As an initial effort, the results of a parametric study of the effects of component losses on cycle efficiency are presented. Considerations in this study include boiler efficiency, turbine internal efficiency, turbine volumetric efficiency, mechanical efficiency, electric generator efficiency, boiler-to-turbine line losses (pressure and heat), and turbine-to-condenser line losses. In addition, proposals are made for experimental determination of RC component performance.

Finally, in addition to the learning assessment and parametric study, future studies are outlined to complete a comprehensive analysis of the RC.

B. Background

At LTU and UE, all mechanical engineering students learn about the Rankine cycle in their required Thermodynamics course during their sophomore or junior year. During their junior year (at UE) or senior year (at LTU), the students put the theory into practice by operating the RC in a required laboratory course. Consequently, it is hoped that every graduating mechanical engineering student will learn and understand electricity generation in fossil fueled plants.

Using the RC contributes to the students' expertise as engineers when they eventually encounter new alternative energy methods that are beginning to emerge. Proponents of alternative energy must understand the basics of electricity generation before they can learn how the process' efficiency can be improved and emissions reduced. Since the majority of U.S. electricity is generated by equipment operating in the Rankine thermodynamic cycle, alternative energy students can use the RC to begin understanding how emerging alternative energy sources are one of the keys to improving the Rankine cycle. The RC allows efficiency studies, and therefore the students will see first hand that electricity generating plants with higher efficiency will use less fuel and release less emissions.

In this paper, the effectiveness of the RC as a learning tool is examined through a student survey. Next a parametric study of the effects of component losses on RC thermal efficiency is examined. Finally, future experimental work is outlined to complete a full characterization of the RC.

2. Rankine Cycler Effectiveness as a Learning Tool/Survey Results

While the RC is the only cost-effective laboratory equipment on the market to introduce students to Rankine cycle power equipment similar to that they may encounter in practice, it is unknown if the equipment is a good learning tool. A study has been initiated to determine if the RC is a worthwhile and practical tool for the students to study basic electricity generation and cycle efficiencies.

Various questions were asked of students on a survey after each had completed the laboratory exercises. Much of the survey is quantifiable using a 5-point Likert scale, but written responses were also gathered. While many different experiments are possible with the RC (see LTU sample laboratory assignment in Appendix B), the survey is general enough that it is likely applicable to any college using the unit. Questions asked on the survey are shown in Appendix C.

A. Preliminary Results

The results listed here are only preliminary, since at the time this paper was written the survey had only been distributed in a few laboratory course sections at LTU. The survey will continue to be distributed at LTU and at UE so that larger sample sizes can be tallied and reported and university-to-university comparisons can be made.

As shown in Table 1, before performing the RC exercise in lab, students did not feel comfortable with the concepts related to the Rankine Cycle. On a scale of 1 to 5, where 1 is “strongly disagree” and 5 is “strongly agree,” the average student response was 2.38. The median was 2 with a standard deviation of 1.06.

Also shown in Table 1, after completing the RC exercise (including the calculations), the students did have a better understanding of the Rankine Cycle scoring an average of 3.63, a median of 4 and a standard deviation of 0.916.

	strongly disagree	disagree	no opinion	agree	strongly agree
Before performing the Rankine Cycler exercise in lab, I felt comfortable with the concepts related to the Rankine Cycle	12.5	**62.5**	0	25	0
After completing the Rankine Cycler exercise (including the calculations), I have a better understanding of the Rankine Cycle	0	12.5	12.5	**50**	25

Table 1. Percentage of students agreeing with the statements concerning the Rankine Cycler™

After rating each part of the exercise, putting a 1 next to the most beneficial, a 2 next to the next beneficial, and a 3 next to the least beneficial, the average results are as follows:

Discussing and using the RC with the instructor – 1.38

Seeing real (lab-scale) components and their operation – 1.75

Performing the calculations/analysis – 2.25

Based on these results, the students did not believe they benefited as greatly from the calculations and analysis as they did from the in-lab exercise. This result is not surprising for three reasons. First, most of the students have already performed the required calculations in their Thermodynamics course. Second, the numbers calculated from the laboratory data are not representative of full-size plant data or of the values that appear in typical textbook exercises and therefore have little meaning to the students. Considering that the students do not have an intuitive feel for real power plant figures, the numbers that they generate have no significant meaning. Third, many students do not enjoy detailed "theoretical" calculations; they are looking for hands-on application. One student recommended "less calculations and more how does it work and why."

For the calculations and analysis ratings, (students put a 1 next to the most beneficial, a 2 next to the next beneficial, etc.) the results are as follows:

average	analysis exercise
1.8	T-s diagram generation
3.2	turbine isentropic efficiency
3.8	first law analysis
4.0	thermal efficiency / heat rate
4.3	condensing tower efficiency
5.3	power and energy
6.2	increasing thermal efficiency

Table 2: Calculation / Analysis Results

As shown on Table 3, the students found the RC as experimental <u>equipment</u> as a useful tool for learning thermodynamics. On a scale of 1 to 5, where 1 is "strongly disagree" and 5 is "strongly agree," the average student response was 4.0, the median was 4.0 and the standard deviation was 1.15.

Also shown on Table 3, the students found the <u>in-lab procedure</u> for using the RC was a useful exercise for furthering their knowledge and understanding of Thermodynamics with an average score of 4.0, a median of 4.5 and a standard deviation of 1.20.

Finally from Table 3, the students found the <u>analysis and calculations</u> associated with the RC exercise were useful for furthering their knowledge and understanding of thermodynamics with an average score of 3.5, a median of 3.5, and a standard deviation of 0.926.

	strongly disagree	disagree	no opinion	agree	strongly agree
The Rankine Cycler as experimental equipment is a useful tool for learning thermodynamics	0	14.3	14.3	28.6	**42.9**
The in-lab procedure for using the Rankine Cycler was a useful exercise for furthering my knowledge and understanding of Thermodynamics	0	12.5	25	12.5	**50**
The analysis and calculations associated with the Rankine Cycler exercise were useful for furthering my knowledge and understanding of Thermodynamics	0	12.5	**37.5**	**37.5**	12.5

Table 3. Percentage of students agreeing with the statements concerning the aspects of the Rankine Cycler™

As a basis for ensuring that the quality of instruction was sufficient and that the equipment was being used in a worthwhile manner, the students rated the instructor's use of the RC. The results are shown in Table 4. On a scale of 1 to 5, where 1 is "unsatisfactory" and 5 is "excellent," the average student response was 4.0, the median was 4.0, and the standard deviation was 0.926.

	unsatisfactory	poor	satisfactory	good	excellent
How do you rate the instructor's use of the Rankine Cycler?	0	0	37.5	25	37.5

Table 4. Percentage of students rating the instructor's use of the Rankine Cycler™

As shown on Table 5, the level of material covered with the RC exercise was rated as just barely advanced with an average score of 2.5, where 1 is "too advanced," 3 is "just right," and 5 is "too easy." The median was also 2.5 and the standard deviation was 0.535.

	too advanced	advanced	just right	easy	too easy
The level of material covered with the Rankine Cycler exercise was:	0	50	50	0	0

Table 5. Percentage of students rating the level of material covered with the Rankine Cycler™

Finally the students found the RC exercise did not significantly increase their interest in the thermal-fluid sciences, nor did it significantly decrease their interest (see Table 6). On a scale of 1 to 5, where 1 is "strongly disagree" and 5 is "strongly agree," the average student response was 2.75. The median was 3.0 and the standard deviation was 1.28. By their senior year, students have already decided where their interests and/or strengths lie. A single laboratory exercise is unlikely to change their perception. The slight challenge in performing the calculations may account for the higher "strongly disagree" response shown on Table 6.

	strongly disagree	disagree	no opinion	agree	strongly agree
The Rankine Cycler exercise increased my interest in the thermal-fluid sciences.	25	12.5	25	**37.5**	0

Table 6. Percentage of students agreeing with the statement concerning their interest in the thermal-fluid science field due to the RC.

Overall, the RC and its associated exercises performed quite well as a learning tool, according to the students. They reported that their knowledge of the Rankine cycle (and its associated thermodynamic concepts) increased. They found discussing and using the RC more valuable than performing calculations with the data. In addition, the level of the material was appropriately challenging for upper-level engineering students.

It should be noted that the RC was evaluated as a learning tool based on an indirect assessment (i.e., a measure of student opinion). To directly assess the students' understanding of the Rankine cycle will require a future evaluation of their graded laboratory reports.

B. Student Comments

While the RC is a good learning tool, the students had some worthwhile suggestions (written on the survey). One student commented, "It would be more beneficial to discuss [the RC equipment] after the [completion of the laboratory report], as the knowledge has sunk-in and [was] applied."

Another student that found the operation of the RC as the most beneficial aspect of the exercise commented, "A picture or model is worth a lot." That same student found the calculations and analysis least beneficial and commented, "Doing the calculations was aggravating. Units should all be [in the] same [unit system]. It's one thing to see and read the theory and another to make sense of a mess of data…."

A student who found the generation of a T-s diagram the most beneficial analysis step commented, “This shows the most information for the amount of work. If you understand the chart it can show (somewhat) most of the other information.” This student found the condensing tower calculation least beneficial and added the comment, “The tower is not very accurate and doesn’t work well.”

Finally a student noted that the equipment should have a method of viewing what is happening inside the components. The student commented, “need see-through panels or cut-aways of a model to see what is really happening inside. I would bet most students could not tell you what the turbine looks like and how it works. One needs to know how it works to understand the process.” It would therefore be useful for Turbine Technologies, Ltd. to have available extra turbine rotors and/or boiler cut-aways that instructors could show and discuss with the students.

C. Keys to Meaningful Instruction

There are a few potential pitfalls to avoid when using the RC as a learning/teaching tool. First, the instructor should gauge the amount of Rankine cycle coverage that the students received in their Thermodynamics course. At a smaller college where all of the students had the same instructor for Thermodynamics, this is a simple task of asking the instructor or looking at the syllabus. At a college where multiple sections of Thermodynamics are offered each semester with a variety of instructors, this task is more difficult. If the students received very little instruction on the Rankine cycle in Thermodynamics, the terminology and experimental process becomes intimidating. Be sure to allow ample laboratory class time to describe and use the RC if this is the case.

The condenser looks very similar to a hyperbolic natural draft cooling tower. Convey to the students that it is not a cooling tower but a very simple atmospheric baffle condenser. It is shaped like a cooling tower for visual impact, and the shape has little to no impact on the heat transfer occurring within the tower. (By the way, the hyperbolic shape of a natural draft cooling tower also has little impact with the heat transfer occurring within the tower. They are built that way “to offer superior strength and resistance to ambient wind loadings[1].”)

While heat rate is more commonly used in the power industry, students typically spend more time examining thermal efficiency. If the students will be using heat rate, be sure to properly introduce the concept and its meaning. The heating value of propane may be useful for this calculation.

One of the toughest tasks for the students while doing the calculation is determining steam properties. Usually students only have access to steam tables in the back of a text book. These tables work fine for classroom calculation, but for actual data, a significant of amount of interpolation is necessary. The excessive interpolation is tedious to the student and not particularly meaningful. Therefore, the students should have access to electronic tables that are accurate.

All of the RC pressure measurements are reported in gage pressure. The students often forget or do not know that steam tables are based on absolute pressure. Forewarn the students of this.

If the students are plotting their results on a T-s diagram, they will have some difficulty. The T-s diagrams that they experienced in their Thermodynamics course have greatly exaggerated scales making them easier to visualize and plot.

Finally, the steam exiting the turbine is sometimes wet (a mixture). Since only pressure and temperature are measured at the turbine outlet, there is no way to determine the steam quality and therefore no way to determine the enthalpy and entropy. It may be best to use settings that ensure superheated steam is exiting the turbine.

3. Parametric Study

A parametric study of the effects of component losses on RC thermal efficiency was performed. There are three purposes for performing this parametric study. First, the Thermal-Fluids Laboratory course at UE requires the students to perform a pre-lab analysis for every laboratory exercise. The pre-lab exercise for the RC involves estimating a thermal efficiency before an actual data-collecting run of the equipment. Because the students do not have a good intuitive feel for real-world Rankine cycle power plant efficiencies, the pre-lab is a daunting if not inane exercise for the students. A parametric study available on an interactive Excel Spreadsheet will help the students generate realistic numbers and compare various component effects on the total system. Second, a parametric study will help to pinpoint what combinations of various component losses account for the poor performance (i.e., low thermal efficiency or high heat rate) of the RC. Finally, the parametric study will give future experimenters a rough guide for the limitations of the RC. Once experimental runs are begun to allow full characterization of the RC, the optimum operating point will be more easily determined and future work/direction for experimentation will be known.

The RC has several significant differences from an ideal or real-world full-sized plant. One of the most significant is the fact that the RC does not use a pump. This means that truly cyclic operation is not possible. It is possible, however, to obtain (limited time) steady flow operation of the turbine and generator. When using the RC, the boiler is filled to about three-fourths capacity prior to operation. The water is heated at constant volume by a flame fueled with liquid propane (LP). The heat addition process under constant volume conditions causes a pressure increase in the boiler. The high pressure steam is piped to the turbine where it expands and drives the electrical generator via a pair of spring shafts connecting the turbine and generator. The low pressure steam (sometimes still superheated) is piped to the "condenser"/cooling tower where it experiences constant pressure heat rejection. A fraction of the water condenses into a catch tube while the remainder escapes from the top of the tower. The steam flow can be maintained for some time period until the boiler pressure falls below an acceptable level. It is important to note that this "no-pump" feature of the RC makes it different from the real-world power plant as well as the ideal cycle.

The other ways that the RC differs from the ideal cycle also show up as differences between the ideal cycle and actual operating power plants. In almost all cases, these are "non-ideal" effects that cause the efficiency (or heat rate) of the real RC to be poorer (*lower* efficiency or *higher* heat rate) than the ideal model. A partial catalog of these effects are given below.

Pumping (recall this does not affect the RC)

The pump process is not isentropic. This is measured by a *pump efficiency*:

$$\eta_{\text{pump}} \equiv \frac{\text{ideal work}}{\text{real work}} = \frac{v\Delta p}{\Delta h_{\text{pump}}}.$$

Boiler/Steam Generator

- The fuel may not be completely burned.
- Some heat is lost to the surroundings (mainly in the exhaust gas and from the casing) instead of being transferred to the steam.
- These effects are quantified by a *boiler efficiency*:

$$\eta_{\text{Boiler}} \equiv \frac{\text{Heat added to Steam}}{\text{Energy in fuel}} = \frac{\dot{m}\Delta h)_{\text{Steam}}}{\dot{m}\,\text{HHV})_{\text{fuel}}}.$$

- There is a pressure drop between the boiler water inlet and boiler steam exit (again, recall this does not affect the RC since there is not a water inlet from a pump).

Turbine/Generator

- There are internal "flow friction" losses in the turbine; the turbine expansion is not isentropic. This is quantified by a turbine internal efficiency:

$$\eta_{\text{turbine}} \equiv \frac{\text{Actual turbine work}}{\text{Ideal turbine work}} = \frac{\Delta h_{\text{turbine}}}{\Delta h_{\text{isentropic,turbine}}}.$$

- Some of the steam bypasses the turbine blades (i.e., it leaks between the wheel and the casing or around the turbine shaft). This can be characterized by a flow efficiency:

$$\eta_{\text{flow}} \equiv \frac{\text{Flow passing through turbine blades}}{\text{Flow entering turbine}}.$$

- There are mechanical friction losses in the bearings in the turbine and generator, which are quantified by a mechanical efficiency:

$$\eta_M \equiv \frac{Power\ delivered\ to\ generator\ rotor}{Power\ generated\ by\ turbine\ wheel}\ .$$

- There are electrical losses and windage losses in the generator. These are characterized by a generator efficiency:

$$\eta_{generator} \equiv \frac{Electrical\ power\ output}{Mechanical\ power\ to generator\ rotor}\ .$$

<u>Fluid Transport</u>

- There is a pressure drop between the pump outlet and boiler inlet. (recall this does not affect the RC since there is not a water inlet from a pump). *Note:* Pressure drop *in* the boiler was listed above under Boiler losses.
- There is a pressure drop between the boiler outlet and the turbine inlet. This can be quite significant since this includes pressure drop across the turbine control valve. *Note*: Some of this pressure drop may be included in the turbine internal efficiency; it all depends on where the "turbine inlet" is defined to be.
- There is a pressure drop between the turbine discharge and the condenser. In the RC, the tube connecting the turbine exhaust to the condenser is of significant length, about 25 diameters.
- There is a pressure drop between the condenser discharge and the pump inlet (not present in the RC).

<u>Heat Loss</u>

- There may be heat losses from all plant components, notably the boiler (already accounted in the Boiler Efficiency), turbine, and piping. Generally, such heat losses are negligibly small, except for the boiler.

In an actual power plant, all of these effects combine with the thermodynamic efficiency of the underlying ideal cycle to give a heat rate of about 10,000 Btu/kWhr (net efficiency of about 34%). Because of the extremely small scale of the RC and the low values of its cycle temperature and pressure, the efficiency of the RC is significantly lower, typically less than 1%.

<u>Results</u>

Experimental data generated to date show that the RC efficiency is near 0.1% and the power generated is about 5 Watts. Combinations of parameters that yield "theoretical" results near these values are therefore the most realistic.

The schematic shown in Figure 5 is used as reference for the state points (e.g., state 3 is the entrance to the turbine). Recall that the RC does not have a pump, but to complete the parametric study, state 1 has been approximated as atmospheric conditions and state 2 uses the boiler pressure and standard room temperature.

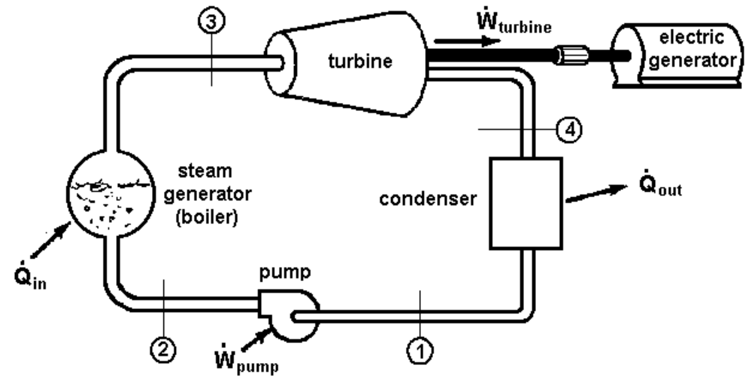

Figure 5: Typical simple Rankine cycle schematic with the state points noted.

To execute a parametric study an Excel spreadsheet was generated. The Excel spreadsheet is interactive and has steam property add-ins so that different operating parameters (experimental data) can be input and the various parameters will be automatically updated.

Typical RC experimental data is shown in Table 7. The fuel flow is 6 L/min of propane and the water mass flow is 0.0073 lb/s. These are the conditions that were used for the parametric study given in this paper. It is a simple task to alter these data for any particular RC run.

	State 1	State 2	Properties at boiler
Pressure (psia)	14.6	114.6	114.6
Temperature (˚F)	71.6	71.6	380

Table 7. Typical RC experimental data used as the starting point for the parametric study.

For the properties at state 3 (turbine inlet), both the heat loss (from the boiler and the piping to the turbine inlet) and the pressure drop (from the boiler outlet to the turbine inlet) were examined. The heat loss was examined for the cases of 0% to 2% in 0.5% increments. Rather than specify a pressure drop, the analysis uses typical (measured) turbine inlet pressures: from 20 psig down to 8 psig in 2 psi increments (pressure drops from about 80 psi to 90 psi). Combining the 4 cases of heat loss with the 7 cases of pressure drop resulted in 28 different sets of properties at the turbine inlet.

Next the turbine outlet pressures were determined by working backwards from the condenser. . Typical pressure drops from the turbine outlet to the condenser inlet (atmospheric) were used: from 4 psi to 7 psi in 1 psi increments. After turbine outlet pressures were determined, the ideal (isentropic) enthalpy drop across the turbine was calculated. Therefore, 4 different pressure drops with 28 turbine inlet states gives 112 different values for the isentropic enthalpy drop, which is the ideal work delivered to the turbine rotor by the steam. Each of these 112 cases can have an overall turbine/generator efficiency applied to it. (Overall turbine/generator efficiency is the product of: turbine internal efficiency, turbine flow efficiency, mechanical efficiency, and electrical efficiency.) The overall efficiencies used range from 5% to 50% with 5% increments. The 112 isentropic turbine cases with the 10 turbine/generator efficiency cases gives 1120 cases.

Finally, the RC thermal efficiency can be determined. The steam generator (boiler) efficiency is unknown and was assumed to be 85%. Calculated thermal efficiency ranged from 0.01% to 1.8%. Based on the experience of the authors, typical experimental thermal efficiencies range from 0.05% to 0.2%. Combinations of parameters that yield calculated efficiencies in the range of 0.05% to 0.2% most closely reflect the actual performance of the RC. These results indicate that the parametric study does cover the appropriate range of turbine/generator efficiencies. It remains to be determined if the boiler efficiency is accurately reflected.

Upon close inspection of the results from the parametric study, the line pressure drop from the boiler outlet to the turbine inlet appears to be one of the largest contributions to low thermal efficiencies. This pressure drop is largely attributed to an aluminum block fitting used as a portion of the piping for the pressure gauge attachment and the steam admission valve also located along this pipeline. Another large contribution to low thermal efficiencies appears to be the turbine/generator efficiency. Only the lowest values of turbine/generator efficiency (5% to 10%) used in the parametric study yields realistic thermal efficiencies (i.e., 0.05% to 0.2%). The boiler is well insulated and the piping is small, so heat loss seems to have little effect on thermal efficiency.

5. Future Work

A significant amount of experimental work remains to complete a characterization of the RC. This experimental work will be an important contribution to potential customers of the unit, faculty/technicians using the equipment with students, students performing experiments, and for future upgrades by Turbine Technologies, LTD. These following three studies would enhance the usefulness of the RC to determine parameters such as output and efficiency.

1. Component Performance: Experiments should be performed on individual components of the RC. Specifically, turbine efficiencies and boiler efficiencies should be determined for various operating conditions. Boiler efficiency would require exhaust gas temperature and oxygen (O_2) measurements.

2. Optimum operating point: Multiple steady state runs should be performed to determine the optimum operating point of the RC. The optimum operating point will be determined from the turbine/generator performance versus load.

3. Steam flow measurement: One of the largest contributions of error in the analysis of the RC data is the steam flow measurement. Because there is no steam flow measurement device supplied and the RC is a once-through device (i.e., not a true cycle), flow is currently estimated by determining the amount of water used during a run and dividing by the elapsed time. Unfortunately, some water is used for preheating the components as well as some to vent the boiler to atmospheric conditions at the conclusion of a run. In addition, a small, uncalibrated sight glass must be used to ultimately measure the water used. Therefore, a method is being devised to measure the steam flow using the turbine and condenser pipe as a flowmeter.

An additional exercise of considerable educational value would be to conduct a Second Law analysis of the unit. Because of its small scale, together with the rather complete set of thermodynamic data available, the RC is an excellent device for performing a second law analysis. Not only would the students benefit from performing a second law analysis (a topic that receives little or no coverage in the required Thermodynamics courses at LTU and UE), it would also give a better understanding of scaling drawbacks and help identify the major sources of losses.

Finally, to determine the effectiveness of the Rankine Cycler as a learning tool, an indirect assessment was performed (i.e., a measure of student opinion). To directly assess the students' understanding of the Rankine cycle will require an evaluation of their graded laboratory reports.

6. Conclusion

Students were surveyed to assess the RC as a learning tool. Preliminary results show that the RC and its associated exercises performed quite well as a learning tool, according to the students. They reported that their knowledge of the Rankine cycle (and its associated thermodynamic concepts) increased. They found discussing and using the RC more valuable than performing calculations with the data. The level of the material was appropriately challenging for upper-level engineering students. A few keys to successful use of the RC were also given.

A parametric study of the effects of component losses on RC thermal efficiency was performed. The results showed that the range of component losses used in the parametric study accurately reflect experimental thermal efficiencies. Also the parametric study pointed to future experimental work that can be accomplished with the RC. This work will be of benefit to users of the RC, potential customers of the RC, and future upgrades to the RC by designers at Turbine Technologies, Ltd.

In conclusion, the benefits of the RC seem to outweigh the idiosyncrasies of the device. For its relatively low cost, the RC is useful to the mechanical engineering curriculum. Continued studies are being performed to confirm this conclusion.

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Appendices

A. Experimental Apparatus Descriptions[2]

The experimental hardware (Rankine Cycler™) consists of multiple components that make up the necessary components for electrical power generation (utilizing water as the working fluid). These components include:

1. Boiler

A stainless steel constructed, dual pass, flame-through tube type boiler, with super heat dome, that includes front and rear doors. Both doors are insulated and open easily to reveal the gas fired burner, flame tubes, hot surface igniter and general boiler construction. The boiler walls are insulated to minimize heat loss. A side mounted sight glass indicates water level.

2. Combustion Burner / Blower

The custom manufactured burner is designed to operate on either LP or natural gas. A solid-state controller automatically regulates boiler pressure via the initiation and termination of burner operation. This U.L. approved system controls electronic ignition, gas flow control and flame sensing.

3. Turbine

The axial flow steam turbine is mounted on a precision-machined stainless steel shaft, which is supported by custom manufactured bronze bearings. Two oiler ports supply lubrication to the bearings. The turbine includes a taper lock for precise mounting and is driven by steam that is directed by an axial flow, bladed nozzle ring. The turbine output shaft is coupled to an AC/DC generator.

4. Electric Generator

An electric generator, driven by the axial flow steam turbine, is of the brushless type. It is a custom wound, 4-pole type and exhibits a safe/low voltage and amperage output. Both AC and DC output poles are readily available for analysis (rpm output, waveform study, relationship between amperage, voltage and power). A variable resistor load is operator adjustable and allows for power output adjustments.

5. Condenser Tower

The seamless, metal-spun condenser tower features 4 stainless steel baffles and facilitates the collection of water vapor. The condensed steam (water) is collected in the bottom of the tower and can be easily drained for measurement/flow rate calculations.

6. Data Acquisition (Note: Newer RC models have an updated system that will operate through the USB port of any newer PC.)

The experimental apparatus is also equipped with an integral computer data acquisition station, which utilizes National Instruments™ data acquisition software (modified 2004 models).

The fully integrated data acquisition system includes 9 sensors. The sensor outputs are conditioned and displayed in "real time"- on screen. Data can be stored and replayed. Run data can be copied off to floppy for follow-on, individual student analysis. Data can be viewed in Notepad, Excel and MSWord (all included).

The system is test run at the factory prior to delivery and the "factory test run" is stored on the hard drive under the "My documents" folder. This file should be reviewed prior to operation, as it gives the participant an overview of typical operating parameters and acquisition capability.

7. Sensors

Nine (9) sensors are installed at key system locations. Each sensor output lead is routed to a centrally located terminal board. A shielded 64-pin cable routes all data to the installed data acquisition card. This card is responsible for signal conditioning and analog to digital conversion. Software and sensor calibration is accomplished at the factory prior to shipment.

Installed sensor list includes:

- Boiler pressure
- Boiler temperature

- Turbine inlet pressure
- Turbine inlet temperature
- Turbine exit pressure
- Turbine exit temperature
- Fuel flow
- Generator voltage output
- Generator amperage output

8. Overall System Dimensions

Length:	48.0 inches (122 cm)
Width:	30.0 inches (77 cm)
Height:	58.0 inches (148 cm)

B. LTU laboratory exercise calculations/analysis

After completing a 2 or 3 minute steady state run at around 3 to 4 Watts, the following data reduction is completed by the students:

1. The measured or weighted re-fill mass of water represents the boiler's total steam production during your run. This can be correlated as the steam rate by dividing the weight of the water replaced by the time duration of your run.
2. Create a T-s diagram showing the actual cycle and the ideal or Rankine cycle for the steady-state process.
3. Provide a first law analysis of each stage of the actual process.
4. Calculate the isentropic efficiency for the turbine.
5. Calculate the thermal efficiency for the entire process. Also calculate the heat rate for the plant during your experiment. You will need the heating value of propane and the fuel flow rate.
6. Calculate the tower efficiency. The purpose of the tower is to reclaim the working fluid (in this case water). In other words, the amount of condensate collected, minus the starting amount of water, gives an indication of the effectiveness of the cooling tower, or tower efficiency. What was the condensing tower efficiency for your experiment?
7. You were able to record the instantaneous values of voltage and amperage. What is the average power produced? What is the total energy that was produced during your experiment?
8. Suggest some practical methods to increase the thermal efficiency of the apparatus (with little to no expense (money or power)).

C. Student Survey Sample

Following is the survey/questionnaire distributed to the laboratory students.

The following survey is used purely for assessment. It will remain confidential and will not contribute to your grade. Be honest in your responses. The goal of this survey is to assess the effectiveness of the Rankine Cycler as a learning tool. The equipment, the experimental process, and the analysis/calculations will be assessed.

I took Thermodynamics in: Fall Spring Summer of (year) _________ Grade: ____

I took Fluid Mechanics in: Fall Spring Summer of (year) _________ Grade: ____

I took Heat Transfer in: Fall Spring Summer of (year) _________ Grade: ____

The Rankine Cycle was covered in my Thermodynamics course. Yes ____ No _____

The Rankine Cycle was covered in my Thermodynamics course. Yes ____ No _____

Before performing the Rankine Cycler exercise in lab, I felt comfortable with the concepts related to the Rankine Cycle:

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

After completing the Rankine Cycler exercise (including the calculations), I have a better understanding of the Rankine Cycle.

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

Rate each part of the exercise that you found most beneficial. Put a 1 next to the most beneficial, a 2 next to the next beneficial, and a 3 next to the least beneficial.

_____ Seeing real (lab-scale) components and their operation
_____ Discussing and using the Rankine Cycler with the instructor
_____ Performing the calculations/analysis

For your most beneficial aspect listed above, why was it most beneficial?

For your least beneficial aspect listed above, why was it least beneficial?

Rate the analysis/calculation parts of the exercise that you found most beneficial. These are found in the hand-out under "Data Reduction" and are listed as 2 through 8 (#1 is not included here as it is simply an essential.). Put a 1 next to the most beneficial, a 2 next to the next beneficial, etc.

_____ 2. T-s diagram
_____ 3. first law analysis
_____ 4. isentropic efficiency
_____ 5. thermal efficiency / heat rate
_____ 6. condensing tower efficiency

_____ 7. power and energy
_____ 8. decreasing heat rate

For your most beneficial aspect listed above, why was it most beneficial?

For your least beneficial aspect listed above, why was it least beneficial?

What analysis/calculations should be added, if any?

The Rankine Cycler as experimental <u>equipment</u> is a useful tool for learning thermodynamics.

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

Suggested changes?

The <u>in-lab procedure</u> for using the Rankine Cycler was a useful exercise for furthering my knowledge and understanding of Thermodynamics.

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

Suggested changes?

The <u>analysis and calculations</u> associated with the Rankine Cycler exercise were useful for furthering my knowledge and understanding of Thermodynamics.

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

Suggested changes?

How do you rate the instructor's use of the Rankine Cycler?

Unsatisfactory	poor	satisfactory	good	excellent
1	2	3	4	5

The level of material covered with the Rankine Cycler exercise was:

Too advanced		just right		Too easy
1	2	3	4	5

The Rankine Cycler exercise increased my interest in the thermal-fluid sciences.

Strongly disagree	disagree	no opinion	agree	strongly agree
1	2	3	4	5

The students were also asked for "Additional comments/observations."